Computed Tomography Scanning and Geophysical Measurements of the Salina Formation from the #36 Brine Well

30 November 2018
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Cover Illustration: Computer tomography images of the Salina formation with corresponding core photos, depths of 6,656 to 6,608.5 ft.

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https://edx.netl.doe.gov/dataset/salina-well
Computed Tomography Scanning and Geophysical Measurements of the Salina Formation from the #36 Brine Well

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NETL-TRS-21-2018

30 November 2018

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<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D</td>
<td>Two-dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>Three-dimensional</td>
</tr>
<tr>
<td>CT</td>
<td>Computed tomography</td>
</tr>
<tr>
<td>EDX</td>
<td>NETL's Energy Data eXchange</td>
</tr>
<tr>
<td>MSCL</td>
<td>Multi-Sensor Core Logger</td>
</tr>
<tr>
<td>MSL</td>
<td>Mean sea level</td>
</tr>
<tr>
<td>NETL</td>
<td>National Energy Technology Laboratory</td>
</tr>
<tr>
<td>WVGES</td>
<td>West Virginia Geological and Economic Survey</td>
</tr>
<tr>
<td>XRF</td>
<td>X-ray fluorescence</td>
</tr>
</tbody>
</table>
Acknowledgments

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**ABSTRACT**

The computed tomography (CT) facilities and the Multi-Sensor Core Logger (MSCL) at the National Energy Technology Laboratory (NETL) in Morgantown, West Virginia were used to characterize core of the Salina Formation from a vertical well (Brine Well #36) from Marshall County, West Virginia at a depth of 6,555.6 to 6,719.5 ft. The primary impetus of this work is a collaboration between West Virginia Geological and Economic Survey (WVGES) and NETL to characterize core from multiple wells to better understand the key formations in West Virginia. As part of this effort, bulk scans of core were obtained from the Brine Well #36, provided by the WVGES. This report, and the associated scans generated, provide detailed datasets not typically available for researchers to analyze. The resultant datasets are presented in this report, and can be accessed from NETL's Energy Data eXchange (EDX) online system using the following link: [https://edx.netl.doe.gov/dataset/salina-well](https://edx.netl.doe.gov/dataset/salina-well).

All equipment and techniques used were non-destructive, enabling future examinations and analyses to be performed on the cores. Low-resolution CT images with the NETL medical CT scanner were obtained for the entire core and high-resolution CT images with the NETL industrial CT scanner were obtained for sections of the core. Qualitative analysis of the medical CT images coupled with X-ray fluorescence (XRF) measurements from the MSCL were useful in identifying zones of interest for more detailed analysis. The ability to quickly identify key areas for more detailed study with higher resolution will save time and resources in future studies. The combination of methods used provides a multi-scale analysis of this core and descriptions of the core that are relevant for many subsurface examinations that have traditionally been performed at NETL.
1. **INTRODUCTION**

In this study, the primary objective was to characterize core from depth with methods not available to most researchers. The data is presented in several formats here and online that are potentially useful for various analyses. Little detailed analysis is presented in this report as the research objective was not to do a site characterization, but rather to develop the data for others to utilize and to create a digital representation of the core that could be preserved.

While it is common for commercial entities to perform these characterizations, the resources necessary to conduct these analyses are not always available to the broader interest base, such as state agencies and research-based consortiums. To meet the growing need for comprehensive and high-quality lithologic data for collaborative research initiatives, the National Energy Technology Laboratory (NETL) has used available resources in conjunction with previous techniques and new, innovative methodologies to develop a systematic approach for the evaluation of cores. Bulk scans of core were performed using fast scanning techniques to obtain base-line information on sample condition and characteristics.

The Brine Well #36, located at the geographic coordinates: 39.758101 N, -80.863961 W (Figures 1 and 2), was drilled by PPG Industries as a salt water production well. Core was retrieved from depths of 6,555.6 to 6,719.5 ft and the ground elevation of the well was 639 ft. This brine well, API# 4705100674, was drilled into the Salina Formation, which is upper Silurian in age, and completed October 20, 1980.

This thick salt layer has had renewed interest due to the examination of its properties in regard to possible storage of natural gas liquids along pipeline routes (i.e. Appalachian Storage Hub), specifically for ethane from Marcellus and Utica plays. Groups such as the Appalachian Oil and Natural Gas Research Consortium (Carter et al., 2017) have evaluated sections of the Salina for subsurface storage in the form of cavities created in the salt formation through brine extraction.

The core was divided into four separate cores and 34 boxes.
Figure 1: Location and structure contour map for the Salina F4 salt interval and Brine Well #36. Adapted from the Appalachian Storage Hub Project (2018). The Salina F4 structure contours are relative to mean sea level (MSL). The depth to formation in this area is approximately 6,000 ft below MSL.
Figure 2: Location and net isopach map for the Salina F4 Salt and Brine Well #36. Adapted from the Appalachian Storage Hub Project (2018). The Salina F4 isopach contours give relative F4 interval thickness; it does not include the dolomite-anhydrite zone below the salt or the salt layer below that zone.
2. **CORE DESCRIPTION**

The core contains a number of rock types including evaporites (halite and anhydrite), shale and carbonates. The bulk of the core contains coarse crystalline halite with some anhydrite (black) interbedded with calcareous brown to grey shale and carbonate anhydrite layers and clasts. A detailed log of the core can be found on the following pages, adapted from Dinterman (2017). The core alternates between massive coarse crystallize sections to thinly laminated (occasionally wavy).
**Computed Tomography Scanning and Geophysical Measurements of the Salina Formation from the #36 Brine Well**

**Figure 3: Detailed lithological log of the Salina #36 core from 6,656 to 6,602 ft, adapted from Dinterman (2017).**

<table>
<thead>
<tr>
<th>Depth (ft)</th>
<th>Lithology</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>6556-6560</td>
<td>Halite</td>
<td>Brown-gray calcareous shale, thinly laminated, sometimes wavy, partially replaced by salt &amp; pepper carbonate(?)-anhydrite mixture. The shale is interbedded with the carbonate-anhydrite beds with more shale at the top of the core. Some carbonate filled veins, 65° at 6557.2 (top) 0.4” and 6559.3 (top) 0.8”. Some brown carbonate nodules 0.25”- 1.5” in length near bottom.</td>
</tr>
<tr>
<td>6560-6565</td>
<td>Anhydrite</td>
<td>Brown-gray calcareous shale, 2” massive beds near top, otherwise thin bedded &amp; wavy, alternating with salt &amp; pepper anhydrite and carbonate(?). The fracture zone distributes some of the shale. At 6564.69-6565.29 the fracture zone includes some salt crystals along the fracture zone. At bottom - 0.6” calcareous shale with holes (dissolved salt crystals). Med-coarse salt crystals at top of break.</td>
</tr>
<tr>
<td>6565-6570</td>
<td>Shale</td>
<td>Crystalline halite with small black anhydrite(?), particles intermixed giving the core a dark gray color. Halite crystals coarser at top 0.5”- 1.5” with less anhydrite. Near bottom, halite crystals are smaller 0.25” – 0.5” with more anhydrite making the core a uniform dark gray. Few disoriented (bedding perpendicular to core) calcareous shale fragments.</td>
</tr>
<tr>
<td>6570-6575</td>
<td>Carbonate</td>
<td>Coarse (1.5”) crystals of halite for 1.5”. Below is 0.8” transition zone of mix of halite crystals with pieces of anhydrite and calcareous shale. Bottom is brown gray calcareous shale with thin wavy bedding interbedded and partially replaced with salt &amp; pepper anhydrite-carbonate mix. At 6583.7 to depth, some dumbbell-shaped and irregularly shaped 0.125” white carbonate structures.</td>
</tr>
<tr>
<td>6575-6580</td>
<td>Black</td>
<td>Uniformly coarse (0.25-0.5”) halite crystals with evenly disseminated black anhydrite pieces which give the section a dark gray color. Few salt &amp; pepper anhydrite-carbonate pieces in lower 1/3 of section.</td>
</tr>
<tr>
<td>6580-6585</td>
<td>Salt</td>
<td>Thin brown &amp; gray calcareous shale layers interbedded with thin salt &amp; pepper anhydrite-carbonate layers. At top 1/2 and bottom 1/3 the layers are contorted and almost a breccia. Few 0.5-1” coarse crystalline salt beds at top &amp; bottom mixed with other contorted beds.</td>
</tr>
</tbody>
</table>
Figure 4: Detailed lithological log of the Salina #36 core from 6,605 to 6,645 ft, adapted from Dinterman (2017).
Figure 5: Detailed lithological log of the Salina #36 core from 6,648 to 6,686 ft, adapted from Dinterman (2017).
Figure 6: Detailed lithological log of the Salina #36 core from 6,685 to 6,719 ft, adapted from Dinterman (2017).
2.1 **CORE PHOTOGRAPHS**

Photographs of the nominal 4-in. diameter core, adapted from Dinterman (2017).

![Core Photographs](image)

**Figure 7:** Salina #36 core photographs, from 6,555.6 to 6,564.8 ft; stars indicate geochemical sample location. Approximately 4-in. diameter core.
Figure 8: Salina #36 core photographs, from 6,564.8 to 6,574.2 ft; stars indicate geochemical sample location. Approximately 4-in. diameter core.
Figure 9: Salina #36 core photographs, from 6,574.2 to 6,583.8 ft; stars indicate geochemical sample location. Approximately 4-in. diameter core.
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Figure 21: Salina #36 core photographs, from 6,694.6 to 6,703.5 ft; star indicates a geochemical sample location. Approximately 4-in. diameter core.
Figure 22: Salina #36 core photographs, from 6,703.5 to 6,712.6 ft; stars indicates geochemical sample location. Approximately 4-in. diameter core.
Figure 23: Salina #36 core photographs, from 6,712.6 to 6,719.5 ft; stars indicates geochemical sample location. Approximately 4-in. diameter core.
3. **DATA ACQUISITION AND METHODOLOGY**

The core was evaluated using computed tomography (CT) scanning and traditional core logging. CT scans were performed on whole cores to maximize the internal area of the core that could be visualized.

3.1 **CORE LOGGING**

Geophysical measurements of P-wave travel time, magnetic susceptibility, and attenuated gamma counts can be obtained with a Geotek® Multi-Sensor Core Logging (MSCL, Figure 24) system on a competent core. For the Salina core the P-wave velocity and magnetic susceptibility were measured and are reported. Additionally, the system was used to measure bulk elemental chemistry with a built-in, portable X-ray fluorescence (XRF) spectrometer. For a full description of the MSCL capabilities at NETL, please see Crandall et al. (2017).

![Figure 24: Representation of generalized MSCL with all attached instruments. From Geotek Ltd., Geotek Multi-Sensor Core Logger Flyer, Daventry, UK (2009).](image)

3.1.1 **Magnetic Susceptibility**

Magnetic susceptibility is a measure of the degree of magnetization in the sample. Due to the large core diameter, the Magnetic Susceptibility Point Sensor was used. The Magnetic Susceptibility Point Sensor works by passing samples under the sensor, where an oscillator circuit produces a low intensity alternating magnetic field (~80 A/m RMS and 2 kHz) and is changed according to magnetic susceptibility of the sample. The measurement unit used is dimensionless (abbreviated simply as SI units) and is based on the original calibration, which is done via stable iron oxides, and reference minerals which have known ranges of susceptibility (Table 1) (Geotek Ltd. Multi-Sensor Core Logger Manual, Version 05-10).
Table 1: Magnetic susceptibility values for common minerals (Modified from Geotek Ltd. Multi-Sensor Core Logger Manual, Version 05-10, 2010)

<table>
<thead>
<tr>
<th>Mineral</th>
<th>X ($10^{-6}$) SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>9</td>
</tr>
<tr>
<td>Calcite</td>
<td>-7.5 to -39</td>
</tr>
<tr>
<td>Halite, Gypsum</td>
<td>-10 to -60</td>
</tr>
<tr>
<td>Illite, Montmorillonite</td>
<td>330 to 410</td>
</tr>
<tr>
<td>Pyrite</td>
<td>5 to 3,500</td>
</tr>
<tr>
<td>Haematite</td>
<td>500 to 40,000</td>
</tr>
<tr>
<td>Magnetite</td>
<td>1,000,000 to 5,700,000</td>
</tr>
</tbody>
</table>

3.1.2 P-wave Velocity

P-wave velocity measurements are performed to measure the acoustic impedance of a geologic sample with compressional waves. Acoustic impedance is a measure of how well a material transmits vibrations, which is directly proportional to density and material consolidation. An example of a material that has a high acoustic impedance would be air, with a wave speed of 330 m/s, whereas granite would have low acoustic impedance, with a wave speed of >5,000 m/s. These measurements can be proxies for seismic reflection coefficients and can be translated to field use when doing seismic surveys.

The software associated with the MSCL measures the travel time of the pulse with a resolution of 50 ns. The absolute accuracy of the instrument measurements is ± 3 m/s with a resolution of 1.5 m/s (Geotek Ltd. Multi-Sensor Core Logger Manual, Version 05-10; Geotek Ltd., 2010).

3.1.3 X-ray Fluorescence Spectrometry

In addition to the geophysical measurements a portable handheld Innov-X® X-Ray Fluorescence Spectrometer was used to measure relative elemental abundances. Two suites were run, the Mining-Plus Suite and Soil Suite, at 6 cm resolution for 60 second exposure time per beam. The Mining-Plus Suite utilizes a 2-beam analysis that resolves major elements (Mg, Al, Si, P, S, Cl, Fe, K, Ca, and Ti), minor elements (V, Cu, Ni, Cr, Mn, and Pb), trace elements (Co, Zn, As, Zr, Mo, Ag, Cd, Sn, Sb, Hf, W, and Bi) and an aggregated “light element” (H to Na). The Soil Suite utilizes a 3-beam analysis that resolves major elements (P, S, Cl, Ca, K, Fe, and Ti), minor elements (V, Cr, Mn, Fe, Co, Ni, Cu, and Zn), trace elements (Rb, Sr, Y, Zr, Nb, Mo, Ag, Cd, Sn, Sb, Cs, Ba, Th, U, W, Hg, Pb, and Bi), and a retroactively calculated aggregated “light element” (H to Si) (Figure 25). Elemental abundances are reported relative to the total elemental composition, i.e. out of 100% weight.
The XRF spectrometer measures elemental abundances by subjecting the sample to X-ray photons. The high energy of the photons displaces inner orbital electrons in the respective elements. The vacancies in the lower orbitals cause outer orbital electrons to “fall” into lower orbits to satisfy the disturbed electron configuration. The substitution into lower orbitals causes a release of a secondary X-ray photon, which has an energy associated with a specific element. These relative and element specific energy emissions can then be used to determine bulk elemental composition.
3.2 MEDICAL CT SCANNING

Core scale CT scanning was done with a Toshiba® Aquilion TSX-101A/R medical scanner (medical CT) as shown in Figure 26. The medical CT scanner generates images with a resolution in the millimeter range, with scans having voxel resolutions of 0.43 x 0.43 mm in the XY plane and 0.50 mm along the core axis. The scans were conducted at a voltage of 135 kV and at 200 mA. Subsequent processing and combining of stacks was performed to create three-dimensional (3D) volumetric representations of the cores and a two-dimensional (2D) cross-section through the middle of the core samples using ImageJ (Rasband, 2018). The variation in greyscale values observed in the CT images indicates changes in the CT number obtained from the CT scans, which is directly proportional to changes in the attenuation and density of the scanned rock, i.e. darker regions are less dense. While the medical CT scanner was not used for detailed characterization in this study, it allowed for non-destructive bulk characterization of the core, and thus complimented the MSCL data on the resultant logs.

![Figure 26: Medical CT at the NETL used for core analysis.](image)

3.3 INDUSTRIAL CT SCANNING

Detailed scans of several sections of interest were performed by the North-Star Imaging Inc. M-5000® Industrial Computed Tomography System (Industrial CT) at NETL. The system was used to obtain higher resolution scans with a resolution of (67.9 μm)³ and capture the details of certain features clearly.

The scans were performed at a voltage of 185 kV and a current of 200 μA, which provided the best balance of resolution and energy to penetrate the samples. The samples were rotated 360° and 1440 radiograph projections of the samples were obtained, averaging 5 individual radiographs at each step to create the reconstruction.
3.4 DATA COMPILATION

Strater® by Golden Software® was used to compile the MSCL and medical CT data into a series of geophysical logs. The data used to generate these logs can be accessed from NETL's Energy Data eXchange (EDX) online system using the following link:

4. RESULTS

The following section presents the data collected from the medical CT, industrial CT, and MSCL. The compiled core logs show the processed vertical 2D slices of the medical CT scans, followed by the XRF and geophysical measurements of the core from the MSCL.

4.1 MEDICAL CT SCANS

The core from the Salina #36 Brine Well was scanned with a Toshiba Aquilion TSX-101A/R medical CT scanner at a sub-millimeter core-scale resolution (430 µm by 430 µm by 500 µm). Core was scanned in 2.3 to 2.5 ft or smaller sections obtained from each core box; highly-fractured regions with a true depth in excess of 2.5 ft were often scanned. Detailed information in log books and photographs of cores were used to merge multiple scans of cores when this occurred. In the following images the overall depth for each scanned sub-section of core is listed. Many interesting features can readily be seen in the following images, including interfaces of salt and siltstone, grain size and layering changes, fault surfaces, fractures and clast shape and orientation.

The following images have been processed with a 3D mean filter of radius 2 in the x and y planes and 3 in the axial plane to improve the ability to discern structural features and materials using ImageJ (Rasband, 2018). The unprocessed data is available on EDX.
Computed Tomography Scanning and Geophysical Measurements of the Salina Formation from the #36 Brine Well

Figure 27: 2D isolated planes through the vertical center of the medical CT scans of the Salina #36 core from 6,555.6 to 6,567.2 ft.
Figure 28: 2D isolated planes through the vertical center of the medical CT scans of the Salina #36 core from 6,567.2 to 6,579.0 ft.
Figure 29: 2D isolated planes through the vertical center of the medical CT scans of the Salina #36 core from 6,579 to 6,590.8 ft.
Figure 30: 2D isolated planes through the vertical center of the medical CT scans of the Salina #36 core from 6,590.8 to 6,610.2 ft; missing core from Core 1, Box 9 and Core 2, Box 1 (6,592.8 to 6,605.5 ft).
Figure 31: 2D isolated planes through the vertical center of the medical CT scans of the Salina #36 core from 6,610.2 to 6,621.6 ft.
Figure 32: 2D isolated planes through the vertical center of the medical CT scans of the Salina #36 core from 6,621.6 to 6,633 ft.
Figure 33: 2D isolated planes through the vertical center of the medical CT scans of the Salina #36 core from 6,633 to 6,643.7 ft.
Figure 34: 2D isolated planes through the vertical center of the medical CT scans of the Salina #36 core from 6,643.7 to 6,656 ft.
Computed Tomography Scanning and Geophysical Measurements of the Salina Formation from the #36 Brine Well

Figure 35: 2D isolated planes through the vertical center of the medical CT scans of the Salina #36 core from 6,656 to 6,667.5 ft.
Figure 36: 2D isolated planes through the vertical center of the medical CT scans of the Salina #36 core from 6,667.5 to 6,679 ft.
Figure 37: 2D isolated planes through the vertical center of the medical CT scans of the Salina #36 core from 6,679 to 6,689.7 ft.
Figure 38: 2D isolated planes through the vertical center of the medical CT scans of the Salina #36 core from 6,689.7 to 6,701.4 ft.
Figure 39: 2D isolated planes through the vertical center of the medical CT scans of the Salina #36 core from 6,701.4 to 6,712.6 ft.
Figure 40: 2D isolated planes through the vertical center of the medical CT scans of the Salina #36 core from 6,712.6 to 6,719.5 ft.
4.2  INDUSTRIAL CT SCANS

The industrial CT scans were conducted at a resolution of 67.9 µm. Several of the industrial scans were processed in ImageJ for beam hardening artifacts using an automated correction (BeamHardening_Correction) (Romano, 2018). The result of the correction process is outlined in Figure 41. The corrected greyscale values in the following images were used to isolate and visually differentiate objects of interest in the scans. The increased resolution decreases the amount of attenuation “shadowing” of high density features and allows us to have a better understanding of the geometry of these features.

The premise of isolating features is to first segment out the feature based on its unique greyscale value. Once this isolation has occurred, the next steps are to differentiate multiple isolated features and then combine them into one coherent visual representation. The following images show these feature isolations to enhance the ability of the reader to discern differences observed in the Salina core. Only portions of the core were scanned and analyzed as part of this report because of the time involved in scanning with this system (over 2 hours per scan). Raw CT images are available for additional analysis on [https://edx.netl.doe.gov/dataset/salina-well](https://edx.netl.doe.gov/dataset/salina-well).

![Figure 41: A) Original 2D isolated cross-sectional plane and corresponding plot of greyscale values. Note the increase in values towards the edges of the core. B) Beam hardening corrected 2D isolated cross-sectional plane and corresponding plot of greyscale values. Note the preservation of unique values from the original plot.](image-url)
Figure 42: 2D isolated vertical plane through the industrial CT scan of the Salina #36 core from 6,656.5 to 6,657 ft.

4.3 ADDITIONAL CT DATA

Additional CT data can be accessed from NETL's EDX online system using the following link: https://edx.netl.doe.gov/dataset/salina-well. The original CT data is available as 16-bit tif stacks suitable for reading with ImageJ (Rasband, 2018) or other image analysis software. In addition, videos showing the variation along the length of the cross-section images shown in the previous section are available for download and viewing. A single image from these videos is shown in Figure 43, where the distribution of high density minerals in a cross section of the core around a depth of 6,656 ft is shown. Here, the red line through the XZ-plane image of the core shows the location of the XY-plane displayed above. The videos on https://edx.netl.doe.gov/dataset/salina-well show this XY variation along the entire length of the core.
4.4 COMPiled CORE LOG

The compiled core logs were scaled to fit on single pages for rapid review of the combined data from the medical CT scans and MSCL readings. Two sets of logs are presented for the core; the first set with data from the CT scans and XRF data, and the second set with calculated ratios from the XRF scans and P-wave measurements. Features that can be derived from these combined analyses include determination of mineral locations from magnetic susceptibility and using the XRF to inform geochemical composition and mineral form.

Data from the MSCL that was obtained with P-wave velocity less than 330 m/s has been removed from these logs. This low P-wave velocity is less than the anticipated velocity through air, indicating a highly fractured zone and unreliable readings. The location of these fractured zones was confirmed through visual examination of the core and with the medical CT scanned images.

The elemental results from the XRF were corrected for errors exceeding 2% of the measurement and limited to display the top elemental proportions: Ca, Cl, S, Fe, K (from Soil Suite), and Si (from Mining-plus Suite).

Specifically, trends in elemental ratios can provide insight into mineral composition, oxidation state and depositional setting. Examples include: K/Cl, which provides information on relative abundance of clay minerals and halite; Ca/S, which provides information on relative abundance of calcium carbonates versus anhydrite and sulfides; Fe/S, which provides information on relative abundance of Fe-oxide or hydroxide minerals; and Ca/Si, which provides information on relative abundance of calcium carbonates and anhydrite versus silicates. Magnetic susceptibility can test for more clay-rich intervals that generally have higher values, relative to evaporites and carbonates. Gamma density gives a quick look at differences between low density evaporite intervals and high density calcareous shale. These broad trends can quickly give information on large suites of core and direct more focused research. These logs are presented in the following images, Figure 44 and Figure 45.

Figure 43: Single image from a video file available on EDX showing variation in the 4-in. diameter Salina #36 core from 6,656 to 6,658.5 ft. Image shows the variation in composition within the matrix. Note the brighter (higher density) calcareous shale and the darker (lower density) crystalline halite.
Figure 44: Compiled core log for the Salina #36 core.
Figure 45: Compiled core log for the Salina #36 core with elemental ratios.
5. **DISCUSSION**

The measurements of the magnetic susceptibility, P-wave velocity, XRF, and CT analysis provide a unique look into the internal structure of the core and macroscopic changes in lithology. These techniques:

- Are non-destructive
- When performed in parallel, give insight into the core beyond what one individual technique can provide
- Can be used to identify zones of interest for detailed analysis, experimentation, and quantification
- Provide a detailed digital record of the core, before any destructive testing or further degradation, that is accessible and can be referenced for future studies
6. REFERENCES

Appalachian Storage Hub (ASH) Project, mapping files accessed from


Geotek Ltd. Multi-Sensor Core Logger Manual; Version 05-10; Published by Geotek, 3 Faraday Close, Daventry, Northamptonshire NN11 8RD, 2010. info@geotek.co.uk, www.geotek.co.uk


Romano, C. Automated High Accuracy, Rapid Beam Hardening Correction in X-Ray Computed Tomography of Multi-Mineral, Heterogenous Core Samples. University of Strathclyde, 2018. DOI:10.15129/2fb54088-1187-48f2-832b-ef76cf5e7bc1.
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